MICROWAVE CORRELATIVE-EXTREME FLOWMETER OF DIELECTRIC GRANULAR AND POWDER MATERIALS IN PNEUMATIC TRANSPORTATION

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Abstract: The paper represents results of theoretical and experimental research in the field of constructing noncontact flowmeters of granular and powder materials in pneumatic transportation. The task of flow measurement amounts to measuring the average flow density within the controlled profile and flow velocity. The possibility of testing flow average density by microwave sensors is substantiated. To measure the velocity of material-air flow use is made of correlative-extreme method of processing signals from density sensors in accordance with a specially developed algorithm.

Keywords: Microwave density sensors, correlative-extreme method of velocity measuring, noncontact microprocessor-based flowmeter.

INTRODUCTION

To automate storage operations of processing granular and powder materials it is necessary to obtain accurate, reliable and continuous information about the material flow in pneumatic transportation.

Modern flow measurement technology employs contact and noncontact methods and means of measuring.

Contact flowmeters are unacceptable for controlling the flow of some powder-like materials because of their specific physical-mechanical properties, e.g. tendency to adhering, abrasivity.

The most promising of noncontact methods from the standpoint of accuracy, reliability and easiness of realization is the microwave method [1] of obtaining initial testing data with further statistical processing of info signals from microwave sensors.

It is a matter of general experience that the interaction of microwave-range electromagnetic oscillations with powder-gas flow shows the dependence of emanation's integral characteristics on some physical parameters of the flow: average density, ratio of volumes filled by separate phases. The results of experimental investigations performed show that to obtain initial testing information about the material-air flow discharge the most efficient characteristic of electromagnetic emanation to use is the intensity of the wave propagated through the flow.

This has determined the choice of microwave flow sensor reasonable design.

MEASUREMENT PRINCIPLE

The flow sensor is a set of receiving and transmitting horn antennae consisting of a transmitting horn with a built-in oscillator of the 8-mm wave band attached to the transmission pipeline and a receiving horn with a detector attached to the diametrically opposite side of the pipeline.

Microwave fixed-frequency oscillations through the transmitting horn are sent towards the material-air flow. The oscillations modulated by flow particles are picked-up by the receiving horn and directed to the microwave detector which is a short-circuited stretch of the waveguide; at some distance (approximately $\lambda/4$) from the short-circuiting (back) side of the detector a microwave diode is installed. The intensity of the diode output signal is proportionate to fluctuations of the flow density *p(t)* in the profile under control.

Mass flow is determined according to the equation:

$$Q_{м}(t) = S \times v(t) \times \rho(t), \qquad (1)$$

where S – stands for the cross-section area of the transmission pipeline;
v(t) – the velocity of the material-air flow;
p(t) – the density of the material-air flow.

Consequently, to determine the material flow alongside with the flow density information the information of its velocity is also required. The flow velocity can be determined by measuring the time interval necessary for the flow to move between the two microwave sensors placed on the transmission pipeline at the *l* distance.

The delay time τ_d can be obtained as a result of the correlative-extreme processing of the flow parameters stochastic fluctuations registered by the microwave sensors [2].

If the stretch between the two sensors is considered a linear time-invariant transmission system, then the time characteristic of the transmission on application of the *a(t)* and *b(t)* stochastic signals is defined by the cross-correlation function (CCF) in the following form:

$$K_{ab}(t) = \lim_{T\to\infty} \frac{1}{T}\int_0^T a(t)b(t-\tau_d)dt, \qquad (2)$$

where τ_d – stands for the time delay;
T – averaging time.

In the course of practical measurement expression (2) is followed by the CCF estimation at the terminal time interval *T*:

$$K^*_{ab}(t) = \frac{1}{T}\int_0^T a(t)b(t-\tau_d)dt \ . \qquad (3)$$

The τ_d value determining the CCF maximum corresponds to the time necessary for the flow to travel through the *l* section.

The flow velocity *v* can be found from the expression:

$$v = l/\tau_d \qquad . \qquad (4)$$

To realize the above stated method of measurement it is required to ensure stationarity and ergodicity of the microwave sensors' signals in the measurement interval.

EXPERIMENTAL RESULTS

Experimental testing of the material-air flow density and velocity was carried out on a specially developed unit realized at a concrete product plant's bulk cement storage, which structural diagram is shown in figure 1.

Two microwave sensors were installed at a stretch of the cement air steel tube conveyor (diameter 159 mm) at the distance of 380 mm from one another. For producing experimental sensors use was made of the 50 MW, 37 GHz solid-state microwave М31120Б oscillators, Д 402 diodes, and horn antennae with 30° flare angle.

The first sensor forms the *a(t)* analog function of the density signal, while the second one – the *b(t)* function, shifted in time in relation to the *a(t)* function for the τ_d time value of the transportation lag.

To suppress noise and match with the processing unit input the signals are applied to the correlation meter's inputs through band-pass filters and amplifiers. The correlation meter can simultaneously calculate 100 values of the CCF and change the signal delay pitch *b(t)* from 1 microsecond to 1 second. The CCF values were fixed visually on the digital indicating device, the general view of the CCF was shown on the oscillograph display unit.

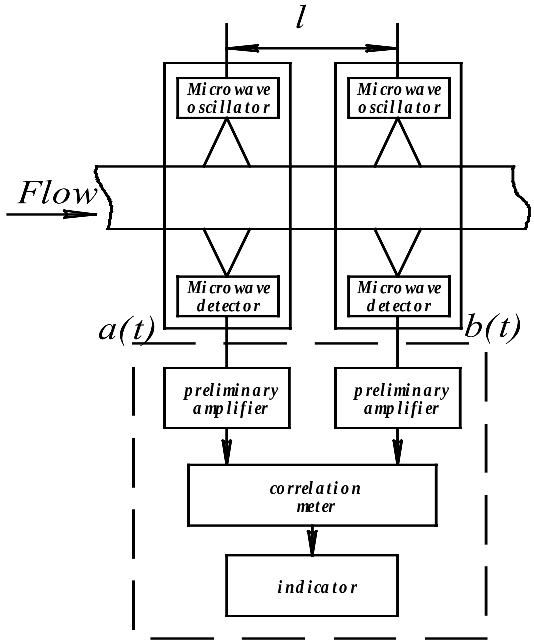

Figure 1. Structural diagram of the flow quantities measurement.

Figure 2 shows the CCF of signals from two microwave sensors calculated by the correlation meter with the time delay pitch of 1 millisecond and the number of initial signal samples of 2^{12}. On the CCF graph we can clearly observe the primary maximum determining the transportation lag of the second sensor signal, it corresponds to τ_d = 17 microseconds. The flow velocity can be found from equation (4) and equals 23 m/s.

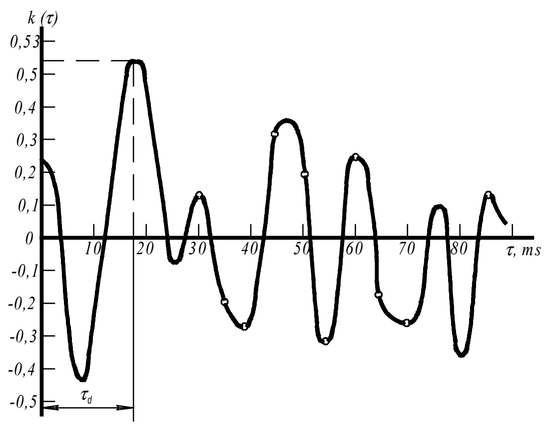

Figure 2. Cross-correlation function of two microwave sensors' signals.

The results achieved enabled development of the software for a specialized pipeline cement flow calculating circuit to be initiated. The development was oriented at the CPU 188-5 micro controller module with the 40 MHz Fastwell Am188ES processor.

PRACTICAL ARRANGEMENT

The CCF calculation algorithm (5) was modified in accordance with the conditions of the Am188ES speed and memory volume minimization and such modification unlike equation (3) enables long duration operations of multiplication to be excluded and replaced by quicker operations of addition and subtraction, while exponentiation operation was replaced by extracting from the memory previously calculated constants.

The algorithm of the correlative-extreme cement flowmeter operation in the real-time mode is represented by the following equations.

The CCF values calculation:

$$K_i = \frac{1}{4}\sum_{i=1}^{N}\left[\left(X_{i+j} + y_i\right)^2 - \left(X_{i+j} - y_i\right)^2\right], \qquad (5)$$

where N – number of the CCF values.

The CCF extremum value is found by comparing the previous value with the following:

$$K_{j+1} - K_j = \Delta K . \qquad (6)$$

The transportation lag is calculated as follows:

$$\tau_d = \Delta t\left(N_{\max} - 1\right), \qquad (7)$$

where Δt – pitch of sampling inputs in time;
N_{max} – number of the CCF extremum value.

The material-air flow velocity is determined as follows:

$$v(t) = \frac{l}{\tau_d(t)} . \qquad (8)$$

The density average value within the access time is found as follows:

$$\rho(t) = \frac{\sum_{i=1}^{N} X_i}{N} . \qquad (9)$$

The material mass flow is calculated as follows:

$$Q_M(t) = Sv(t)\rho(t), \qquad (10)$$

where S – cross section area of the transportation pipeline.

The material mass is determined as follows:

$$M = \int_0^T Q_M(t)d(t), \qquad (11)$$

where T – measurement time interval.

Integration operation in the microprocessor-based mass calculator is replaced by adding flow rate values determined within the time of sampling.

On the basis of the algorithm given above a program for the microprocessor-based cement mass flowmeter system has been developed.

The program consist of the following modules:

LOAD – initial system loading; *ANDIG* – module of timer interruptions processing, accumulation of arrays *X,Y; ALLK* – the CCF values calculation; *MAXK* – the CCF extremum calculation; *DEFRO* – density determination; *DEFQ* – determination of velocity and flow rate; *ACMAS* – mass accumulation; *BIDEC* –conversion of mass value into binary decimal code; *INDMAS* – mass indication.

The sequence of carrying out modules is given in the timing diagram shown in figure 3 (conditionally logical unit level corresponds to module activation).

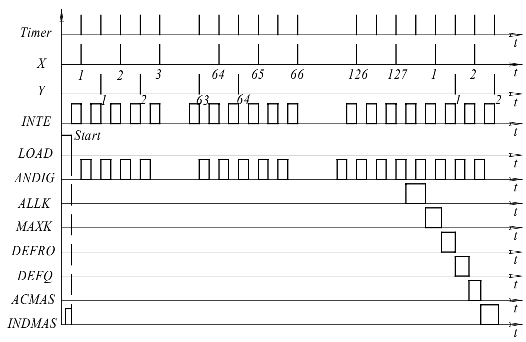

Figure 3. Time sequence of carrying out the program of real time mass flow calculation.

The diagram also shows timer signals, halt approvals HLTA and interruption enables INTE.

Structural diagram of the master program including the above given modules is shown in figure 4.

While starting the system the initial loading module given the conventional name *LOAD* is carried out, the module can be initiated either by a reset signal or by zero interrupt from the control panel, in this module in addition to initial setup values of variables and stack the initial mass value is indicated on the system display.

The loading procedure consists in typing in user-specified parameters' values from matrix or AT-compatible keyboard, converting them into usable format and sending to memory for further use by other program modules.

Upon completion of the initial loading AD converter starting signal is sent and accumulation of value files *X* and *Y* necessary for calculation of the CCF values takes place.

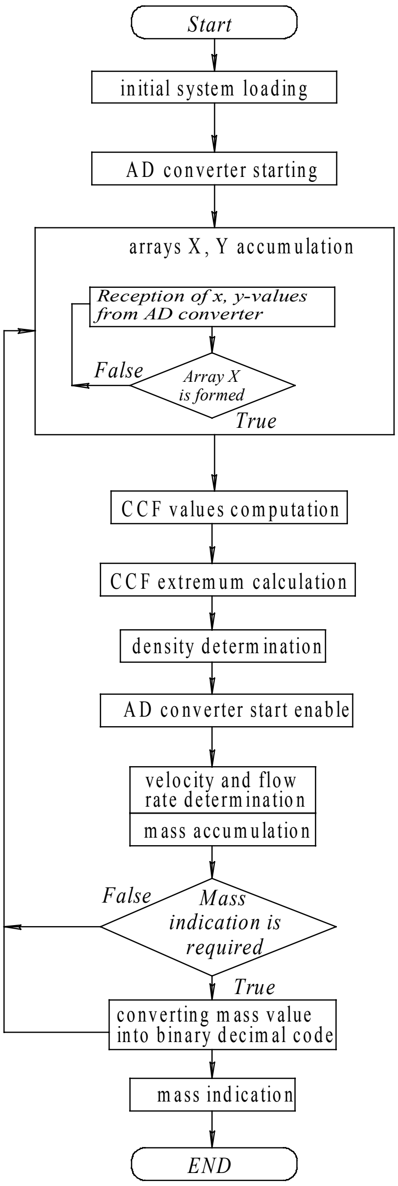

Figure 4. Structural diagram of the master program.

The files X and Y having been accumulated the program as if splits into two "channels". In the first one the current file X and Y is being processed, while in the second – next file X and Y is being accumulated (in case of interrupt signal from AD converter). Processing of the current file X, Y is performed in *ALLK* module where all CCF values are calculated according to algorithm (5). To speed up the processing square values in equation (5) are not calculated but taken from SQUARE table stored in read-only memory. As value X, Y is represented by seven digits, then:

$$(X+Y)^2 \le 2^7 + 2^7 = 2^8 \tag{12}$$

Consequently, *SQUARE* table contains values of square numbers from 1 through 2^8.

As we are interested only in abscissa of the extremum then only integrand value of the CCF is calculated, division by T, centering and normalization are not performed.

While realizing *ALLK* module *MAXK* module is carried out where by method of searching the CCF extremum is found.

To find out the transportation lag use is made of equation (7), and as the timer operation period is known there is no necessity to calculate τ_d value, it equals number of the CCF extremum.

Next module to carry out – *DERFO*. In this module the flow density is calculated in accordance with the following equation:

$$\sigma = (X_1 + X_2 + \ldots + X_N) \;/\; N \tag{13}$$

As the number of samples *X(N)* is divisible by two the division by N is carried out by mere shifting and this also reduces the processing time.

For further processing the current file X, Y is of no use any more, that is why AD converter is started and accumulation of fresh values X, Y instead of previous one is enabled.

To find out the velocity (module *DEFQ*) use is made of equation (8), but instead of l value *LEN 100* is given including both distance between the sensors and correction factors used as the correction for calculating final mass value.

In the course of experimental research it has been determined that the flow transportation lag does not exceed 30 milliseconds, therefore in the timer interval of 1 millisecond the array of τ_d values are within the limits of 1 to 63. This circumstance allows the velocity value not to be calculated but taken from the table in accordance with the corresponding τ_d value. The table is stored in the ROM and called *RATE.*

The flow rate is determined in *DEFQ* module according to equation (10). For this purpose the program of multiplying byte numbers is used.

Mass accumulation (module *ACMAS*) is carried out by simple multibyte addition of flow rate values. If in the process of accumulation change of mass value reaches the values displayed, module *INDMAS* indicating new mass value is activated. Conversion of the mass value from binary form to displayed binary-decimal one is executed in module *BIDEC*, where for the purpose of conversion use is made of the ROM table containing the power of two in binary-decimal form, and this enables the time of conversion to be reduced significantly.

Physical realization of the noncontact correlative-extreme flowmeter is based on the CPU 188-5 microcontroller module with 40 MHz Am188ES Fastwel processor. Structural diagram of the flowmeter is shown in figure 5.

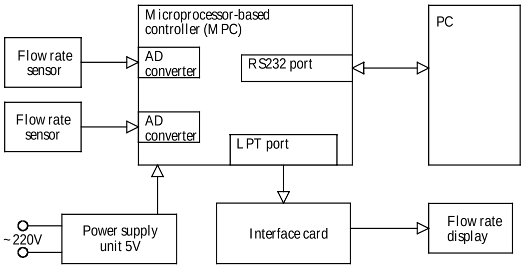

Figure 5. Structural diagram of the microprocessor-based flowmeter.

Information from the microwave sensors is send to analog-digital converters of the microcontroller. According to the algorithm given the MPC calculates the flow rate value and transfer received data to flow rate liquid-crystal display and control PC through RS-232 interface zero-modem cable.

CONCLUSION

Principles of constructing noncontact dielectric material-air flow meters for use in pneumatic transportation based on the microwave method of flow density measurement and the correlative-extreme method of its velocity measurement have been worked out. The flowmeter has been realized as a physical unit (hardware). The presented results of the flowmeter experimental tests carried out in laboratory and plant conditions make it possible to conclude that it meets the production process requirements in accuracy and reliability of operation as well as easiness of adaptability to technological procedures.

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